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ERUPTION STYLE SENSITIVITY TO CRYOMAGMA-VOLATILE COUPLING IN CONDUITS ON ENCELADUS AND OTHER OCEAN WORLDS

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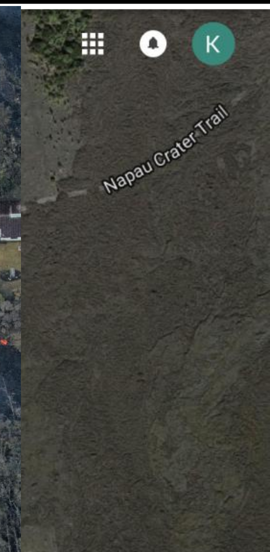
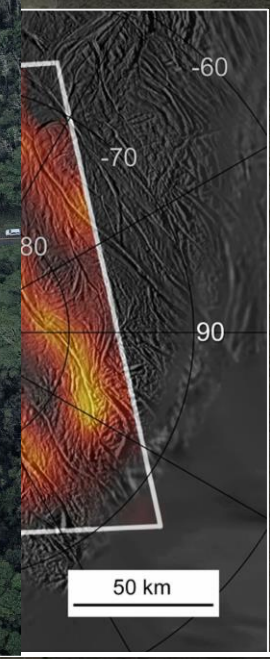
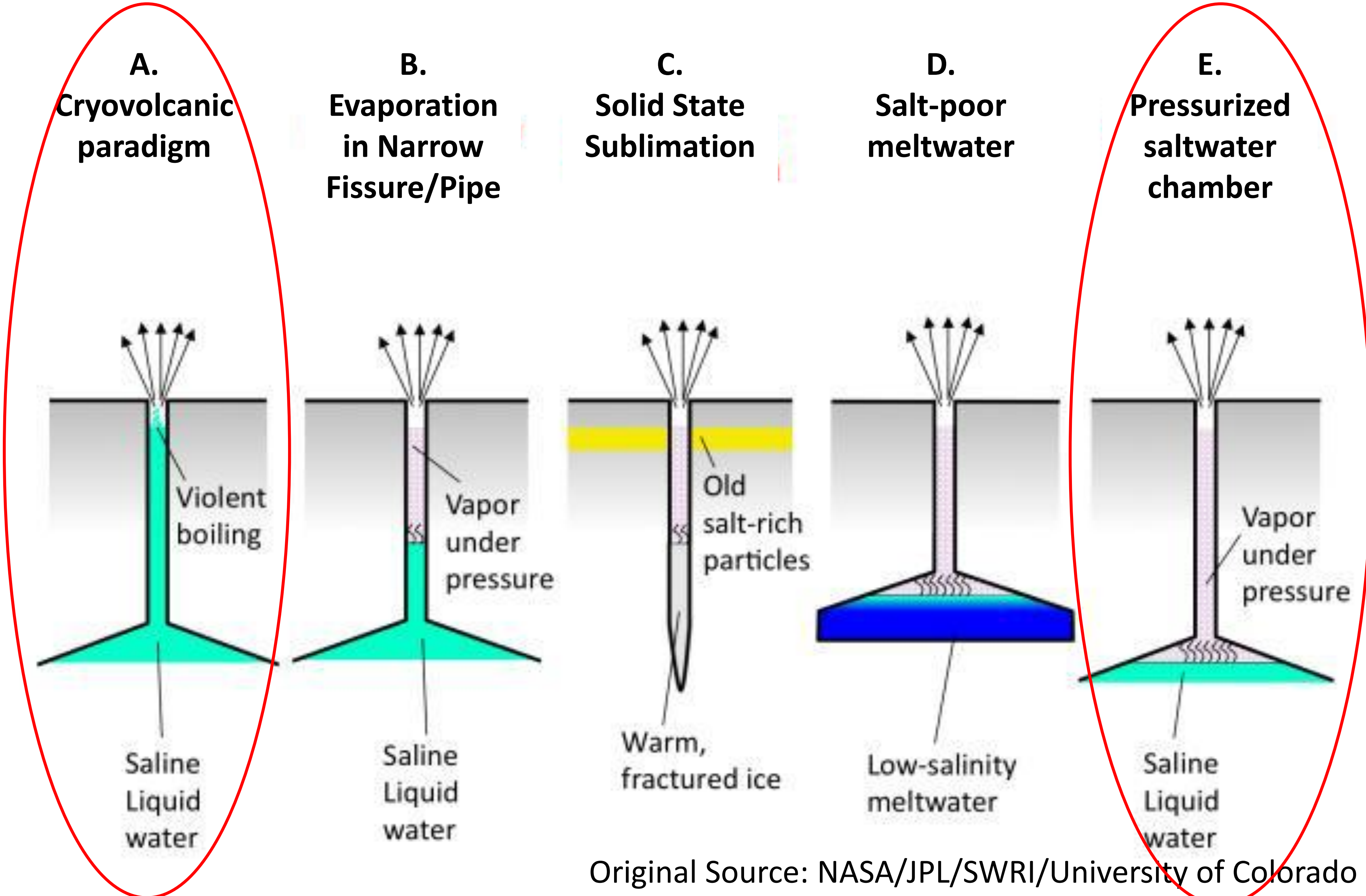
INITIAL THOUGHT: FISSURE ERUPTIONS





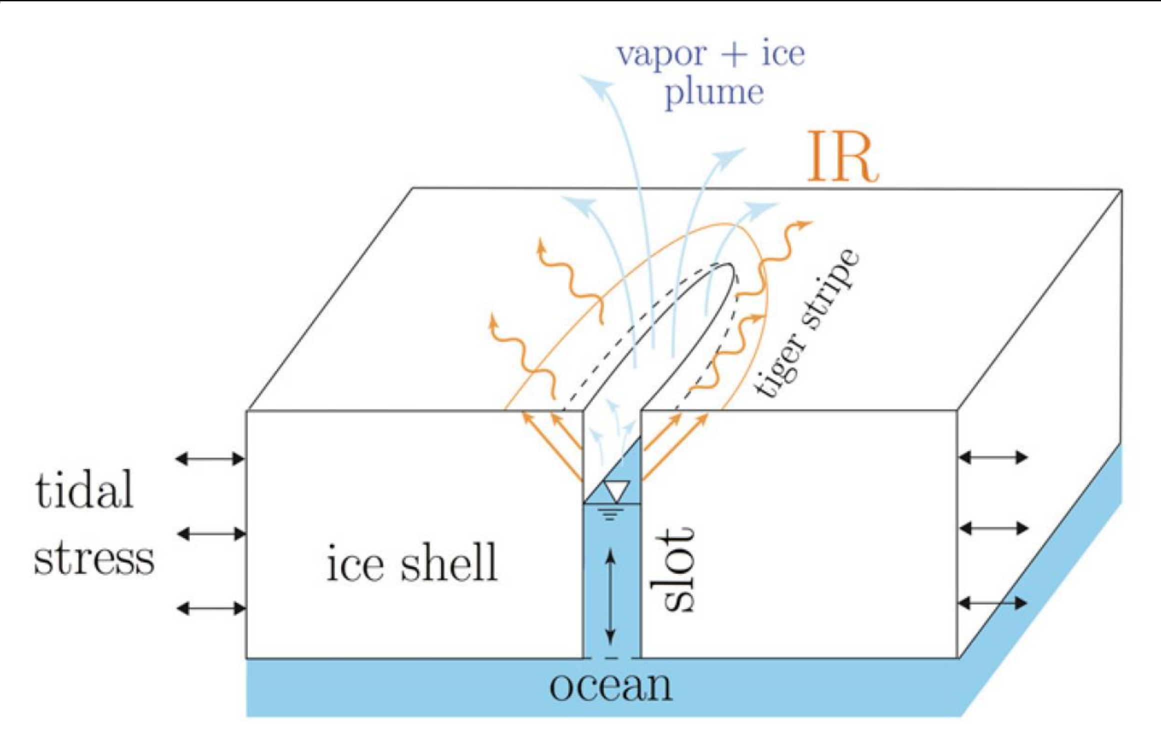
Source: Washington Post

Plume Vent Models



Original Source: NASA/JPL/SWRI/University of Colorado

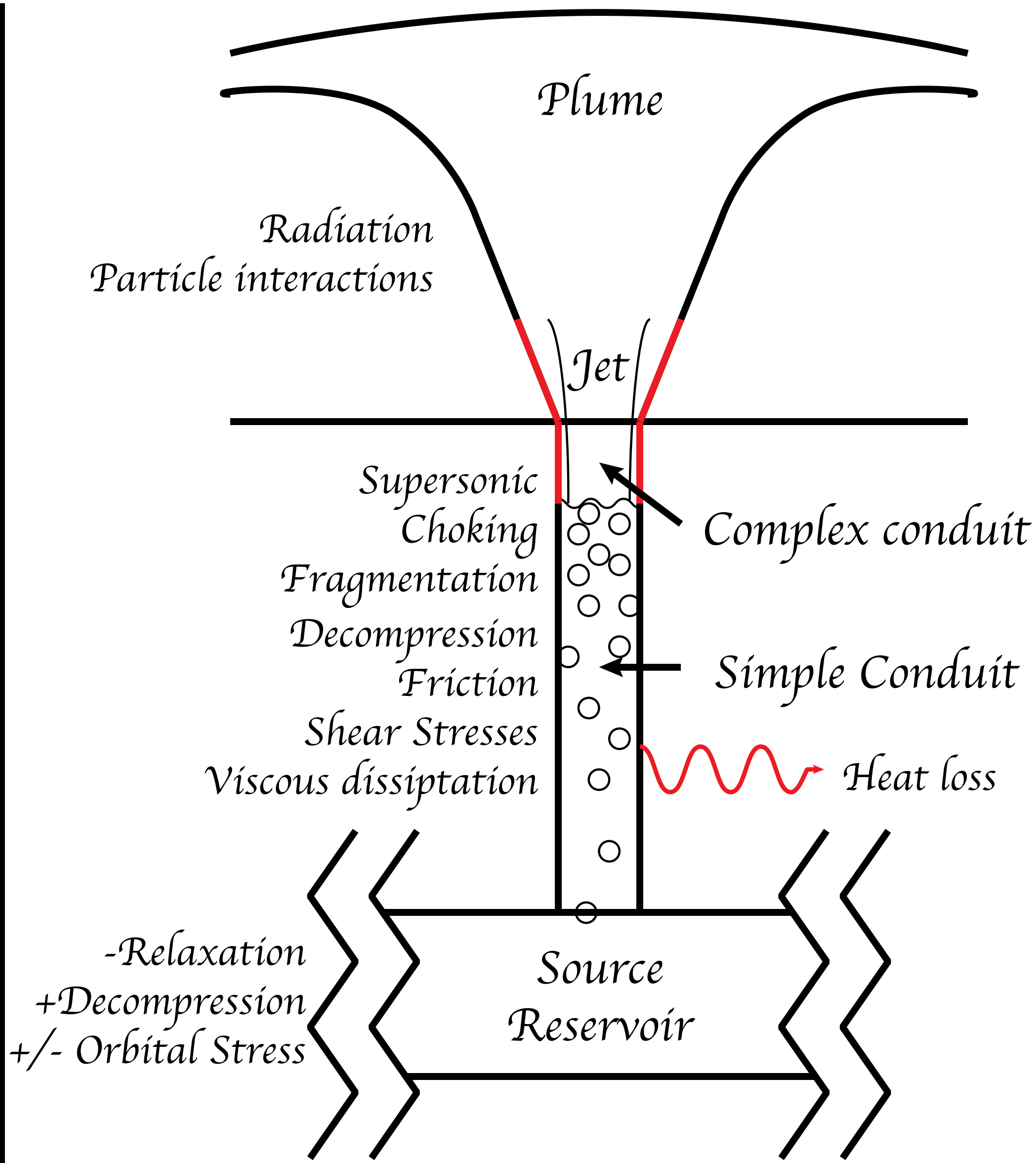
KITE & RUBIN MODEL



- Kite & Rubin (2016) solved critical issues in the boiling models, most critically making them hydraulically plausible and thermodynamically stable.
- Their elegant approach conveniently solves the anomalous thermal output, the pumping process dissipating far more energy than other models.
- No consideration of vent structure, need for converging-diverging nozzle neglected. Condensation should cause slot to evolve.
- Rise speed of water is low and volatile phases should concentrate, but these are not dealt with explicitly. Given abundances in Waite et al. (2017), it is unlikely that any volatile could be saturated in the ocean.
- Eruptants should be highly rarefied, assuming 5-m width, 500 km length of slots, and ~200 kg/s water flux. Eruption velocities should be low, with water vapor dominated by a Maxwell-Boltzmann distribution. u_{RMS} ~ 615 m/s, which is insufficient to account for the >1000 m/s observed (Hansen et al., 2011). Taken together, the water vapor density above the slot would be 1.3 x 10^{-7} kg m^{-3}, with a mean free path of ~1 km.

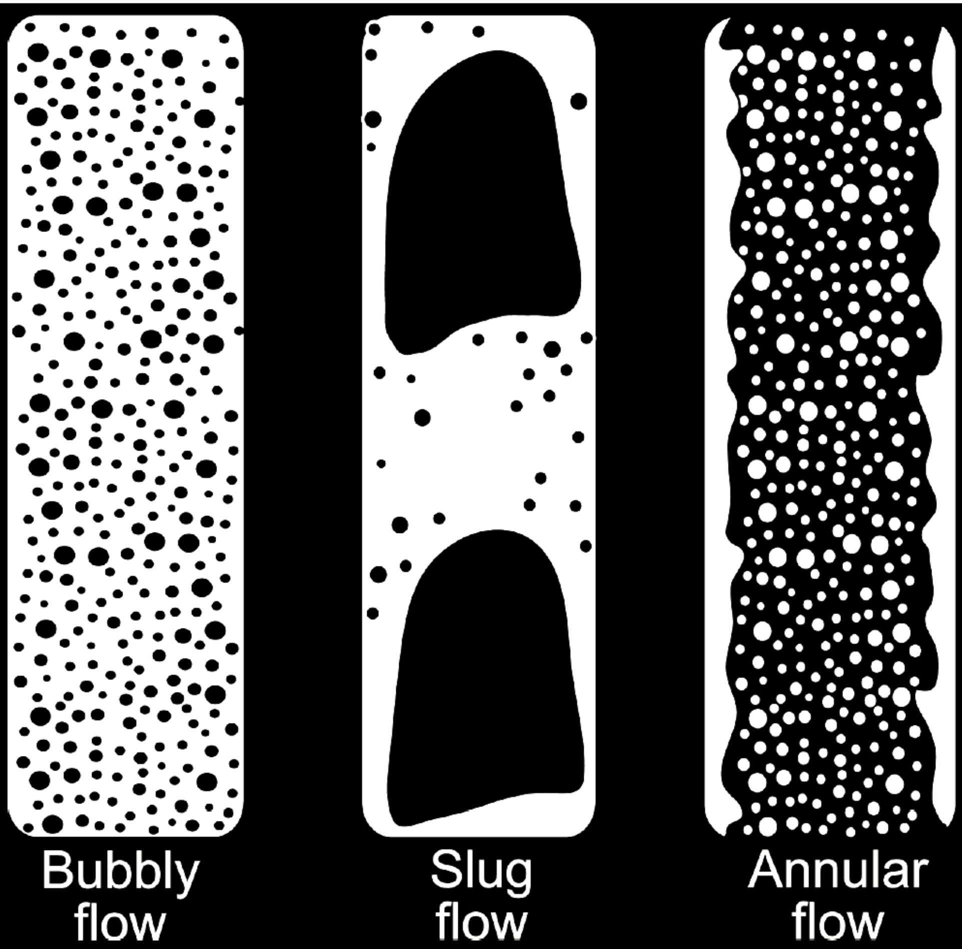
EXPLOSIVE VOLCANISM

- Most terrestrial volcanic eruptions are gas driven. Buoyancy plays an important role in gas-driven eruptions of or within a fluid medium. Exsolution and expansion of gas driven ascent and eruption. Much of work done by expanding gas becomes kinetic energy.
- Could similar happen on Enceladus?



GAS-DRIVEN BUBBLY FLOW

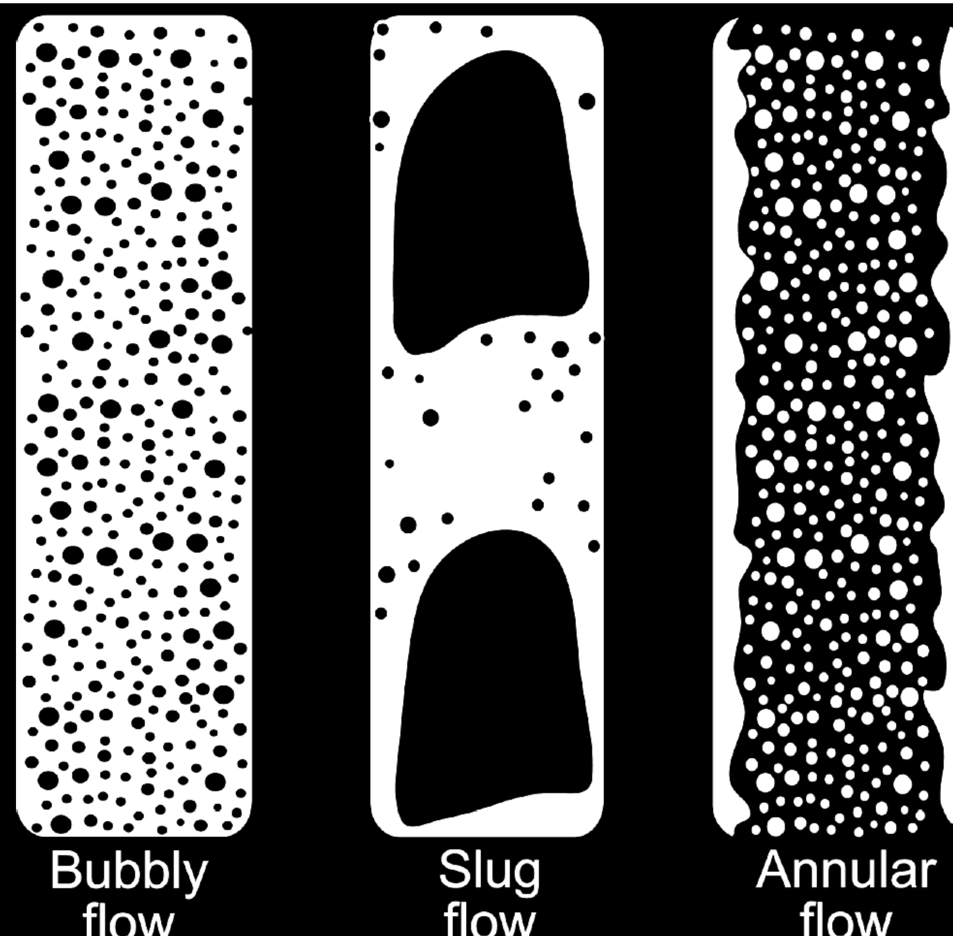
- The extent to which expanding gases drives liquid to ascent is a critical influence on the eruption style. Gas bubbles sometimes separate from the liquid flow.
- If bubbles rise independently of the magma, the erupted materials becomes more gas-rich.
- Bubbles may also accumulate and merge, usually causing either separate fumarolic activity, or non-steady flow (e.g. Strombolian eruptions), typically in inclined conduits.
- The force of viscosity of a bubble rising through a liquid can loosely be modeled by Stokes Flow. A derivative used by Gonnermann and Manga (2012) is presented to estimate terminal velocity, u_t.
- For larger bubbles (Davies & Taylor, 1950), terminal velocity has an upper limit of $u_t \sim 2/3 \sqrt{(g R)}$.



$$U_t = \frac{R^2 g\left(\rho_m - \rho_g\right)}{3\eta_0} \frac{\eta_0 + \eta_g}{\eta_0 + \frac{3}{2}\eta_g}.$$

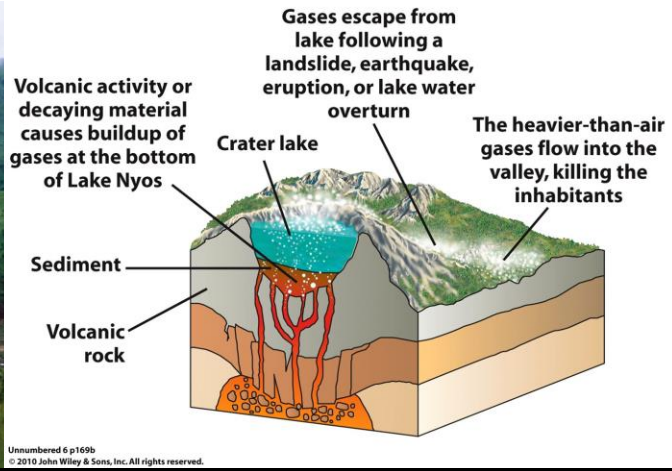
WHAT DO THE BUBBLES DO?

- For bubbles and magma to remain dynamically coupled, ideally terminal velocity, u_t << u, the conduit velocity.
- Rise speeds of small bubbles in water on Enceladus are higher than for basaltic activity on Earth by a factor of ~33x, even in Enceladus' low gravity, due to the very low viscosity, ~8.9 x 10^4 Pa s, c.f. ~10 Pa s for basalt. However, larger bubbles rise 10x slower than on Earth, due to the lower gravity. A bubble capable of rising at 1 m/s would be over 10 m across!
- For a dynamically coupled supersonic flow, conduit velocities are controlled primarily by the internal speed of sound at the conduit throat. Sounds speeds in 2-phase gas-liquid flows are typically lower than either component, usually varying from 10s to 100s of m/s (using Lorenz, 2002).
- However, this doesn't help with the initially static liquid case.



$$U_t = \frac{R^2 g\left(\rho_m - \rho_g\right)}{3\eta_0} \frac{\eta_0 + \eta_g}{\eta_0 + \frac{3}{2}\eta_g}.$$

LIMNIC ERUPTION: LAKE NYOS



- Lake Nyos, 8 days after the CO2-saturated lake exploded, erupting violently, before collapsing and flooding adjacent valleys with dense CO2 gas and water droplets.
- It is assumed that the bottom (208 m depth) of Lake Nyos was completely saturated or supersaturated in CO_2 at ~2 MPa, similar pressures to those predicted in Enceladus' ocean.
- Zhang (1996, 2000) has found that water remains entrained in ascending exsolved CO_2 plume, with a modeled exit velocity of ~56 m/s, and a fountain height of ~160 m. This is consistent with a minmum column height of ~120 m based on distribution of dead animals (Sigvaldason, 1989). Other modeling assumptions give very similar results, typically within a factor of 2.
- If water remains entrained in rising CO_2 at Lake Nyos, it seems reasonable to assert that it could happen on Enceladus, especially if a volatile is saturated at the ocean inlet. Exit pressures are likely lower, and bubble rise velocities would be 10-100x smaller.

MODELING CONDUIT FLOW

- Various modelers have developed approaches that simultaneously treat the thermodynamics, fluid mechanics and sometimes chemistry of an eruption of materials through a conduit.
- Mitchell (2005) uses a 1.5-D axially symmetric solution of the Navier-Stokes equation, coupled with adiabatic thermodynamics and Henry's Law based equilibrium degassing model.
- This has been modified for multi-phase water-based systems to work in entropy rather than enthalpy space. This is because a lot of the interesting thermochemistry happens during flows in which single species exist in multiple phases.
- Some solutions are approximations, based on analytical or less analytical solutions, as these are often more illustrative of general behavior.
- This model breaks down for supersonic flow, as it does not consider the impact of shocks and waves.

Mass: $$\frac{\mathrm{d}\rho}{\rho} + \frac{\mathrm{d}u}{u} + \frac{\mathrm{d}A}{A} = 0$$

Energy: $$T\,ds - P\,dv - \sum \mu_i\, d\,N_i + u\,du + g\,dz = 0$$

Momentum: $$\rho u \mathrm{d}u + \mathrm{d}P + F\mathrm{d}z + \rho g \mathrm{d}z = 0$$

A steady-state 1-D approach using conservation of mass, momentum and energy.

Velocity: $$\frac{\mathrm{d}v}{\mathrm{d}z} = -\frac{1}{\rho u}\left[\frac{\mathrm{d}P}{\mathrm{d}z} + \rho g + F\right]$$

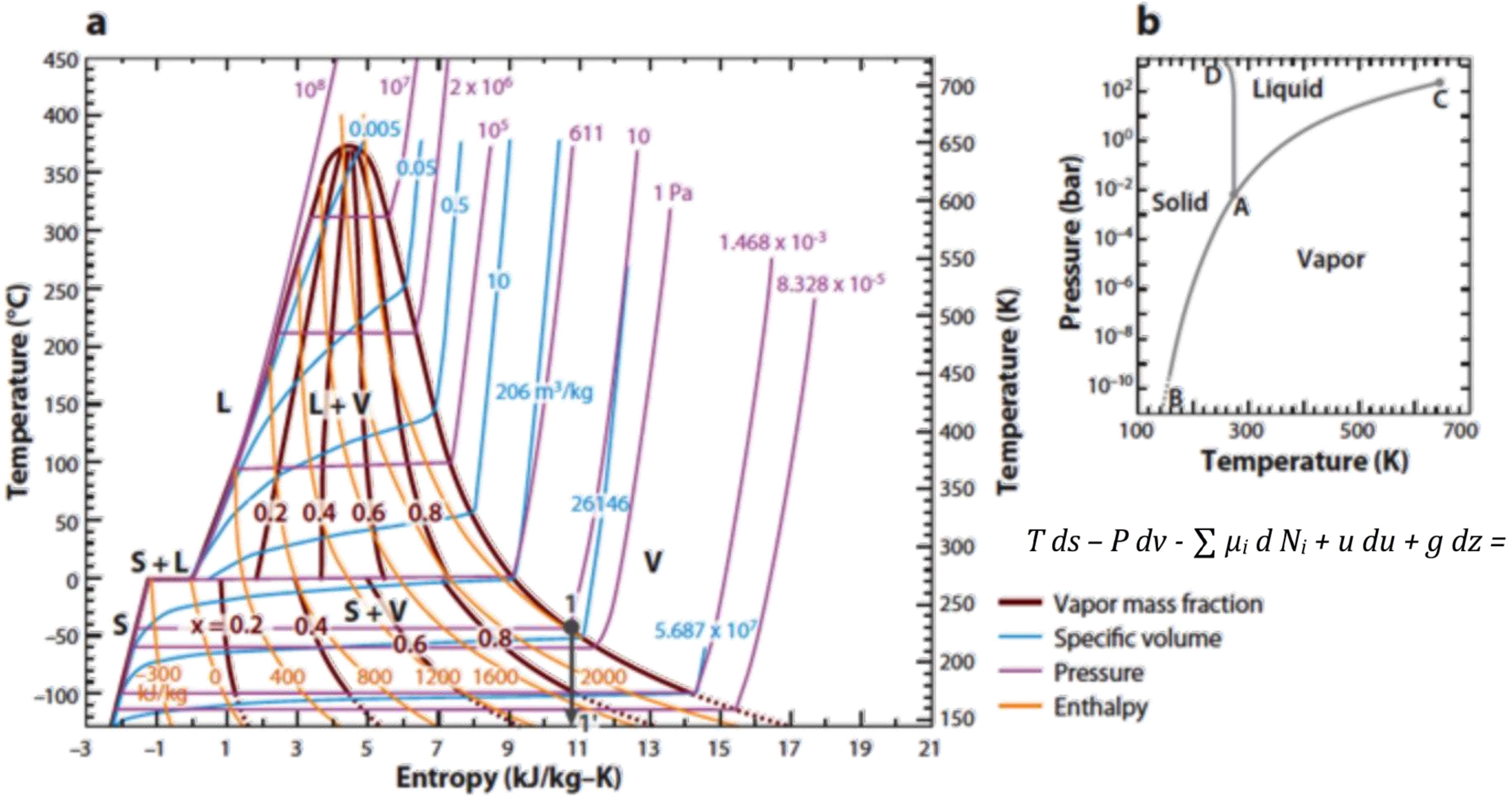
Temperature: $$\frac{\mathrm{d}T}{\mathrm{d}z} = \frac{1}{c_\mathrm{p}}\left[\frac{\mathrm{d}h}{\mathrm{d}z} - \frac{m_\mathrm{m}}{\rho_\mathrm{m}}\frac{\mathrm{d}P}{\mathrm{d}z}\right]$$

Pressure: $$\frac{\mathrm{d}P}{\mathrm{d}z} = \frac{\rho g + F - \dfrac{\rho v^2}{A}\dfrac{\mathrm{d}A}{\mathrm{d}z}}{1 - Mach^2}$$

Area: $$\frac{\mathrm{d}A}{\mathrm{d}z} = \frac{A}{\rho u^2}\left[\frac{\mathrm{d}P}{\mathrm{d}z}\left(\frac{u^2}{c^2}\right) + \rho g + F\right]$$

BASIC THERMODYNAMIC TEST

- Water has extremely high latent heats of transition, and so can accommodate vast changes in enthalpy during boiling or freezing.
- Thermodynamics can be applied independently, but care must be taken to test that the assumptions are consistent with fluid mechanics, and the state of the system must be plausible.

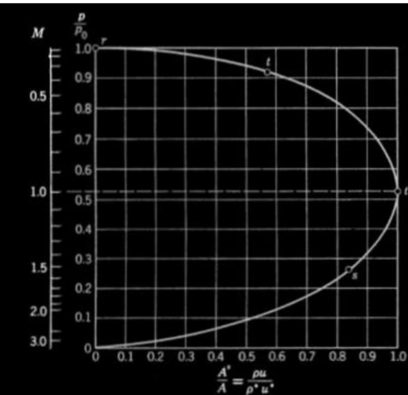


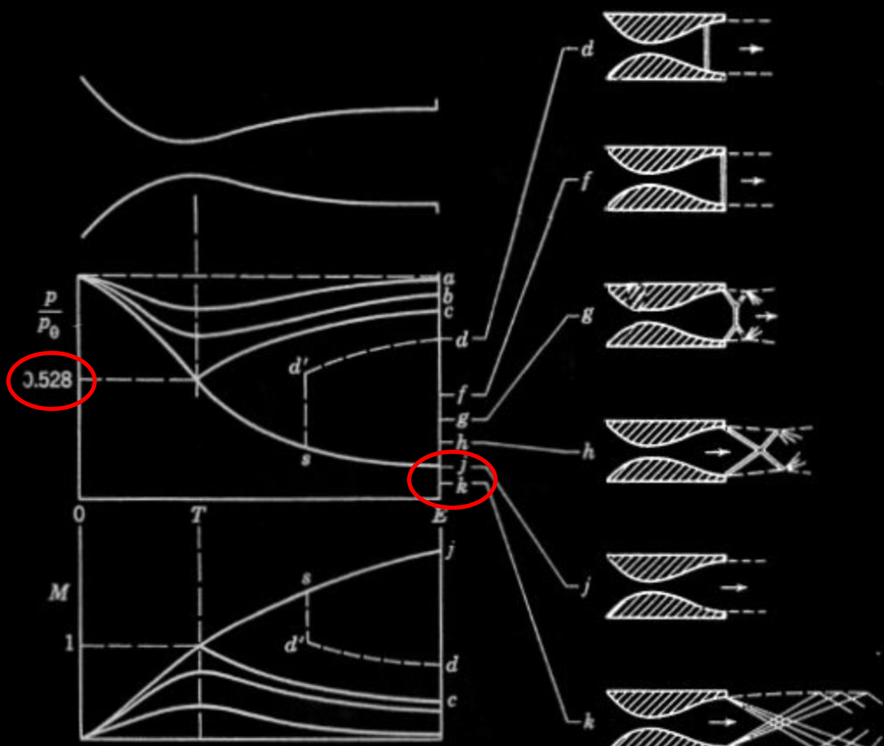
$$T\,ds - P\,dv - \sum \mu_i\, d N_i + u\, du + g\, dz = 0$$

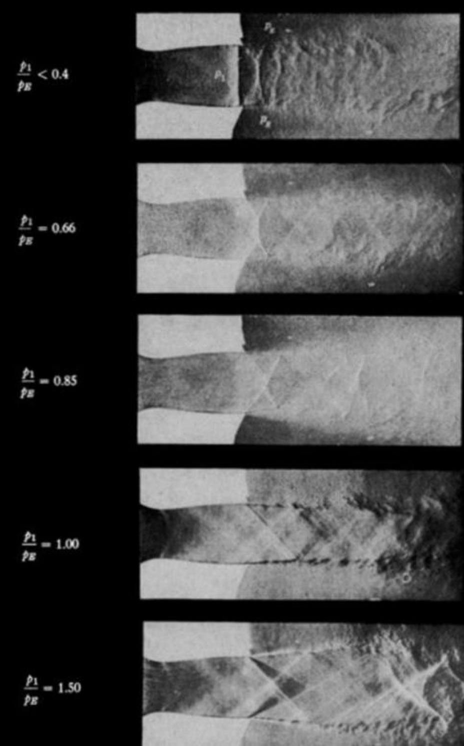
Source: Lu & Kieffer, 2009

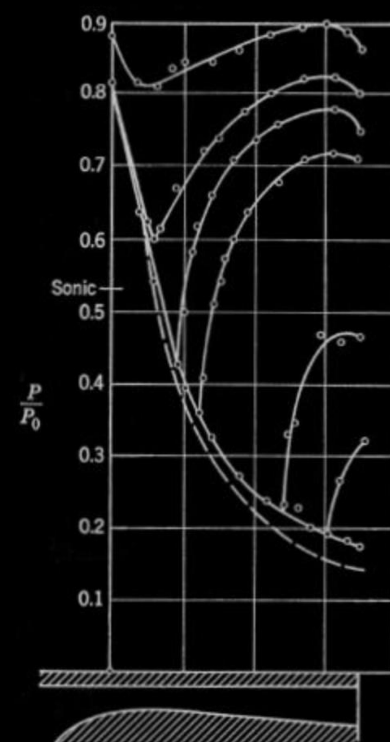
SUPERSONIC JETS ON ENCELADUS

- Nimmo (pers. comm.) commented that the way in which Enceladus' jets change mass flux but not height is consistent with supersonic flow through a nozzle. This is consistent with the very high velocities inferred from remote sensing (e.g. Hansen et al., 2011).
- Mitchell (2005) showed that explosive vents will tend to evolve towards an ideal nozzle shape. If we assume an idealized nozzle, and that the flow can be treated as a pseudogas, we can apply additional constraints.









Figures sourced from: Liepmann, H.W. and Roshko, A. (2001) Elements of gasdynamics. Dover, NY

CONDUIT FLOW MODELING

Chemical and fluid mechanical constraints

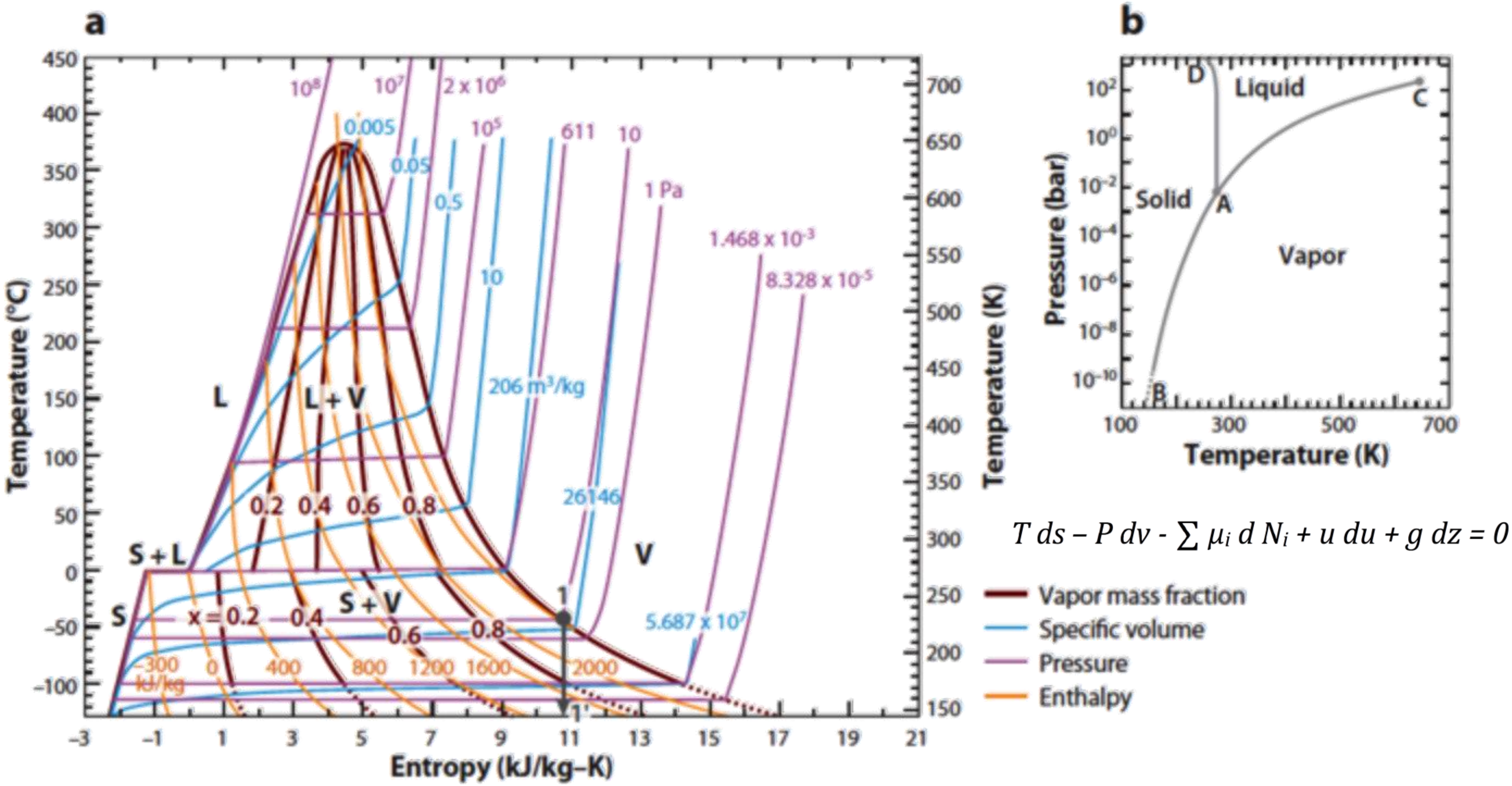
- Erupted molar fractions (Waite et al., 2017): H_2 1.4%, CO_2 0.8%, CH_4 0.19%.
- Lithostatic at depth ~20 km, P_{OCEAN} ~2 MPa.
- Calculated saturation fractions and throat volume gas fractions:
  - P^*/P_0 = 0.53, P_{ex}=0 MPa, P_0~2 MPa, P*~1.2 MPa: H_2 0.29%, CO_2 13%, CH_4 0.5%, ϕ^*~55%, c~69 m/s.
  - P^*/P_0 = 0.53, P_{ex}=3 MPa, P_0~5 MPa, P*~3 MPa: H_2 0.71%, CO_2 31%, CH_4 1.3%, ϕ^*~28%, c~125 m/s
  - P^*/P_0 = 0.1, P_{ex}=0 MPa, P_0~2 MPa, P*~0.2 MPa: H_2 0.29%, CO_2 13%, CH_4 0.5%, ϕ^*~89%, c~47 m/s.
  - P^*/P_0 = 0.1, P_{ex}=3 MPa, P_0~5 MPa, P*~0.5 MPa: H_2 0.71%, CO_2 31%, CH_4 1.3%, ϕ^*~75%, c~54 m/s.
- H_2 is supersaturated in the ocean under all circumstances. Exsolution fractions may exceed those above, as once bubbles or crystals start to form, nucleation becomes easier.
- *Assumptions*: salts, ammonia, etc. neglected. Degree of supersaturation (in absolute pressure difference rather than ratio) remains constant.

Thermodynamical test for freezing

$$T\,ds - P\,dv - \sum \mu_i\, d\,N_i + u\,du + g\,dz = 0$$

- From adiabatic thermodynamics, in no cases is freezing significant (<1%). This is because adiabatic cooling is offset by work done by expanding gases if gases and liquids are both mechanically and thermodynamically well coupled.
- Losses via conduction through walls are inevitable, and not modeled here, but the magnitude cannot account for observed thermal emissions without complete freezing.

POST-THROAT DECOMPRESSION



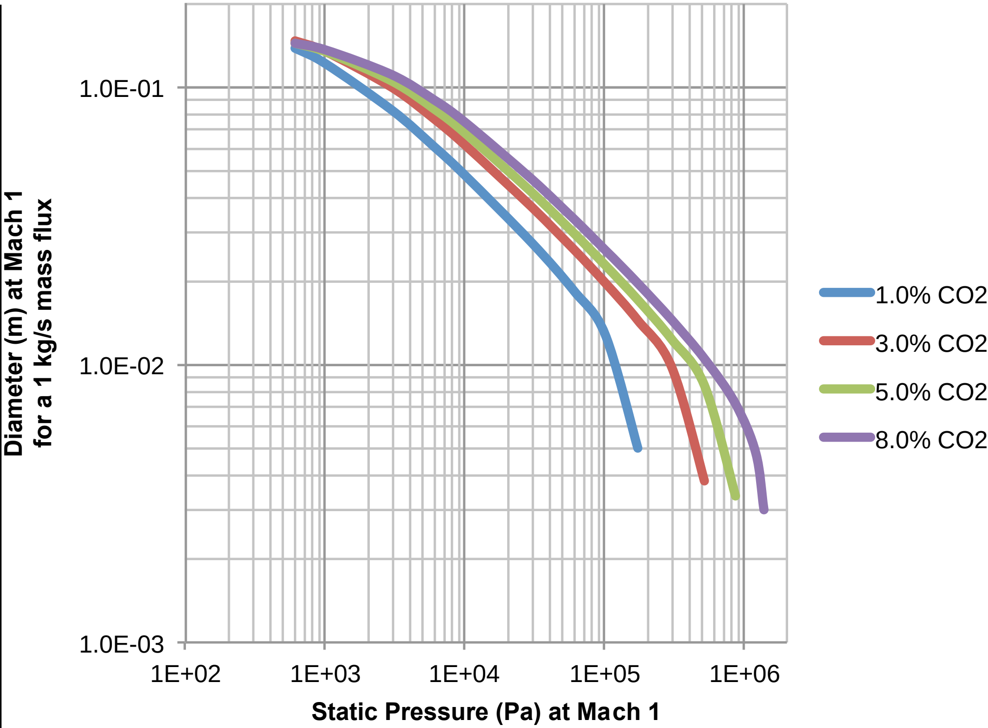
$$T\,ds - P\,dv - \sum \mu_i\, d\,N_i + u\,du + g\,dz = 0$$

- Decompression will be rapid, typically crashing through the critical pressure of water (~611 Pa) within a few to several vent radii of the exit. At these velocities flow will tend to be reversible or adiabatic, resulting simultaneous rapid freezing and boiling at a high solid:vapor ratio. Work done will be massive, and will add considerable kinetic energy to the flow until too rarified.

Source: Lu & Kieffer, 2009

QUESTIONS & CHALLENGES

- Dissolution kinetics are extremely difficult to model, and supersaturation is a free variable.
- Bubble sizes are difficult to predict. Slight phenomenological differences can cause major differences to bubble population.
- The resultant throat is extremely small, <=13 cm diameter at 1 kg/s, possibly much smaller, especially if energetic losses are low. This would be unsurprising given that mass fluxes are less than for Hawaiian vents, but it does mean that heat loss through the walls could be significant.



- Fourier law heat transfer model TBD.
- Supersonic flow modeling TBD.
- Can we demonstrate that bubbles would entrain liquids for even a static starting case?
- Kite & Rubin's elegant pumping model almost certainly does not work for this configuration, bringing us a step back from understanding the thermal anomalies.
- Resultant H_2O solid:vapor ratios are higher than observed (~8:1). However, this can be readily explained by the addition of a sublimation co-plume, given Goguen et al. (2012), which in the extreme case could actually result in vapor fluxes comparable with the plume flux as a whole.

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